

How safe and clean is nuclear? A worst-case check

Lifecycle emissions and deaths per unit of electricity, including the most pessimistic published estimates

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1 What this note does

Two quantities are compared across electricity sources: lifecycle greenhouse-gas emissions (gCO₂eq per kWh) and deaths per TWh from accidents and air pollution. The standard compilations, the IPCC lifecycle reviews and Our World in Data (OWID), already include mining, construction and decommissioning. The question here is how much the picture changes if the most pessimistic published numbers for nuclear are used instead, and why the large assessments do not use those numbers. Every number in the figures is listed with its source in the appendix so that the plots can be recalculated.

A note on wording: where an extreme estimate is described as rejected or criticised, this refers to a cited source saying so. Where a number is not rejected but excluded for a methodological reason, or simply disputed, the text says that instead.

2 Emissions across studies (IPCC SRREN 2011)

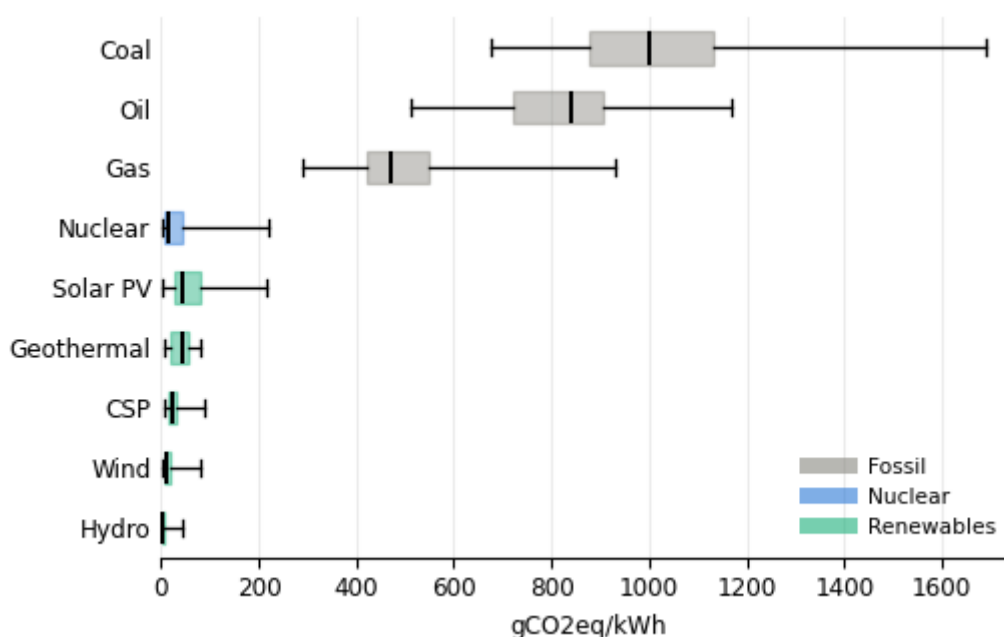


Figure 1: Box = 25th–75th percentile, line = median, whiskers = min–max of published estimates that passed IPCC screening (SRREN Annex II, Table A.II.4). Estimates including land-use change were removed, which excludes reservoir methane from hydro.

The SRREN review screened 2,165 references and kept 296 that met quality and relevance criteria. It explicitly did not screen for outliers or judge input assumptions, so the whiskers include every estimate that passed, high or low. Nuclear's maximum of 220 g is therefore already a pessimistic published value, and it remains below the lowest coal and gas estimates.

3 Emissions with nuclear worst cases (IPCC AR5 2014)

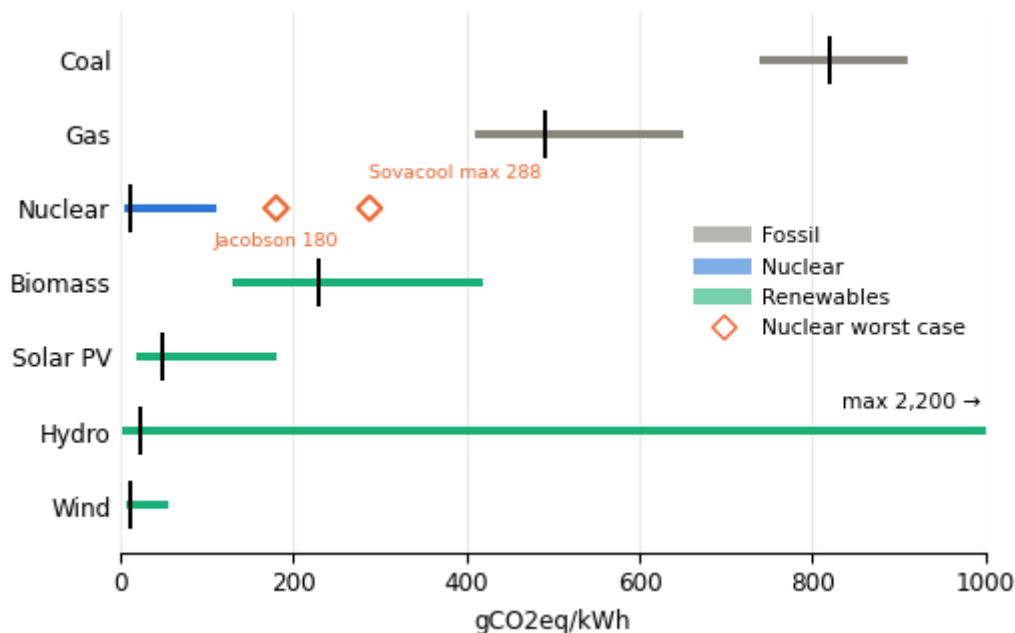


Figure 2: AR5 Annex III, Table A.III.2: whiskers = min-max, line = median (no quartiles published). Hydro's maximum of 2,200 g is clipped. Diamonds: Jacobson (2009) total incl. opportunity-cost emissions (upper value 180) and the maximum of Sovacool's (2008) survey (288).

4 Deaths per TWh

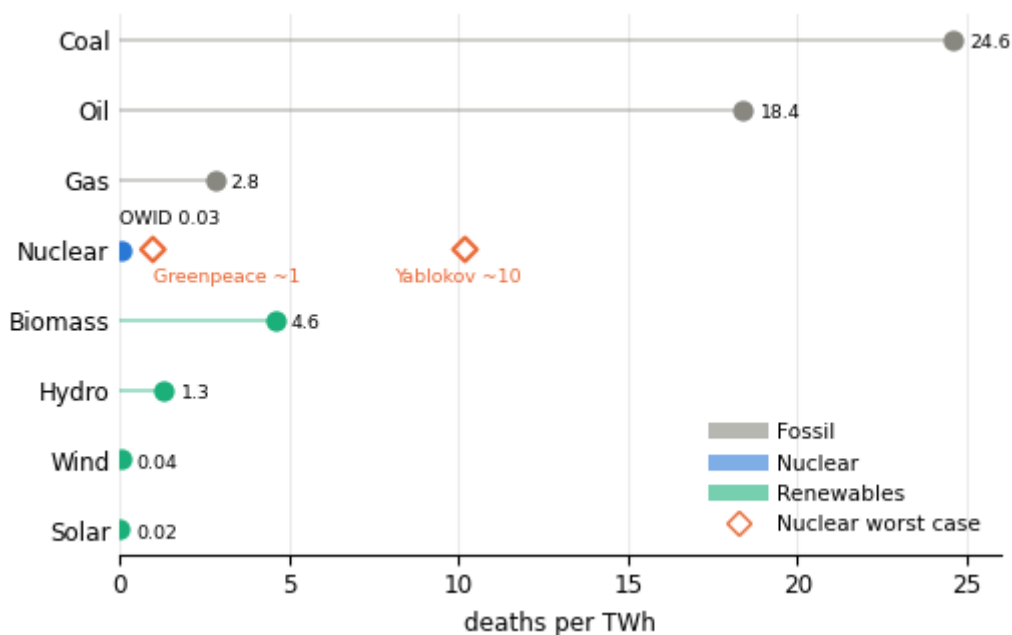


Figure 3: Dots = OWID central estimates (based on Markandya & Wilkinson 2007 and Sovacool et al. 2016). Diamonds = nuclear recalculated with the Greenpeace (2006) and Yablokov et al. (2009) Chernobyl tolls; see Figure 4 and the appendix.

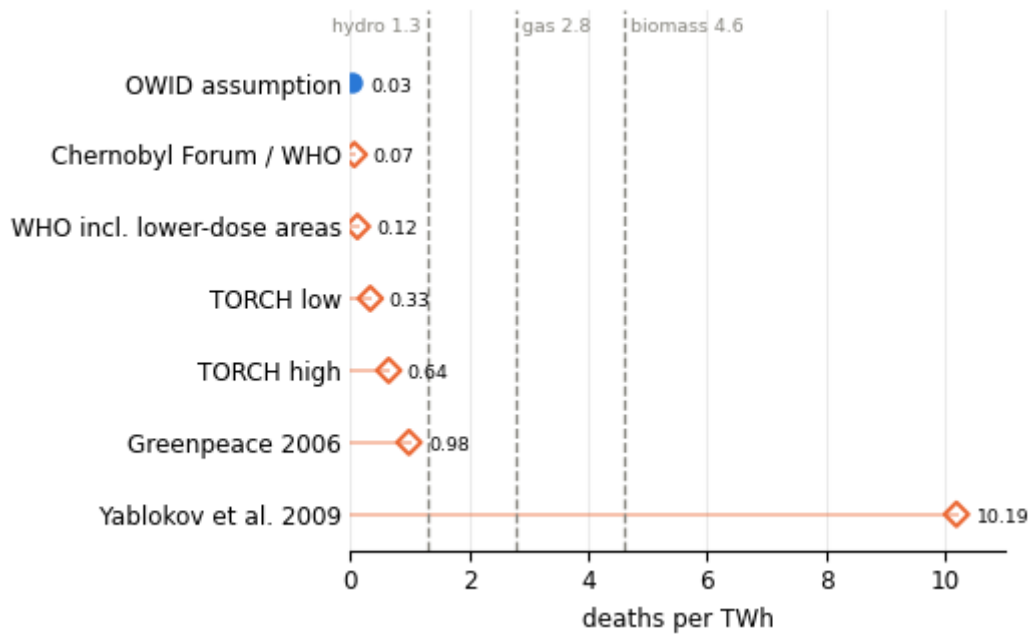


Figure 4: Sensitivity of nuclear's death rate to the assumed Chernobyl toll: (Chernobyl deaths + 2,314 Fukushima deaths) / 96,876 TWh cumulative nuclear generation 1965–2021 (OWID). Dashed lines: OWID central values for comparison.

5 The extreme estimates: arguments and how assessments treat them

5.1 Hydro at 2,200 gCO₂eq/kWh: real, but site-specific

The argument. When a reservoir floods vegetation, organic carbon decays under water, and in oxygen-poor conditions much of it is released as methane. IPCC AR5 attributes hydro's large range mainly to project-to-project variation in these biogenic methane emissions and links high values to a large flooded area relative to the electricity produced (low power density), citing Abril et al. (2005) and Kemenes et al. (2007, 2011). AR5 states that its maximum of about 2 kg CO₂eq/kWh comes from one specific power station analysed by Kemenes et al.

How it is treated. The value is not rejected. AR5 includes it, but notes that the methane distribution is log-normal and has no well-defined minimum or maximum, so its figure shows the 1st–99th percentile. The underlying study (Hertwich 2013) analysed 82 measurements, found methane per kWh spanning from micrograms to tens of kilograms, identified reservoir area per kWh as the most important explanatory variable, and estimated a global average of 85 gCO₂/kWh plus 3 gCH₄/kWh with an uncertainty factor of two. SRREN (Figure 1) had excluded land-use-change emissions altogether, which is why its hydro range is so narrow. The honest summary is that a few shallow, tropical, low-power-density reservoirs are worse than coal per kWh; the median plant is not.

5.2 High nuclear lifecycle emissions (Storm van Leeuwen & Smith; Sovacool 2008)

The argument. Storm van Leeuwen and Smith built a detailed bottom-up account of every step of the fuel chain and argued that energy use, and therefore emissions, rise steeply as uranium ore grades decline. Their estimates were roughly 84–166 gCO₂/kWh depending on version (as tabulated by Sovacool 2008). Sovacool's 2008 survey of 19 qualifying studies reported a range of 1.4–288 g and a mean of 66 g, attributing emissions to fossil-fuelled construction, enrichment and mining.

How it is treated. Sovacool himself noted that the Storm van Leeuwen and Smith estimate “has not been universally accepted”, summarising Dones (2007), who argued that their treatment of some supply-chain emissions was inconsistent and that they may overestimate the energy required. The NREL harmonisation study (Warner & Heath 2012) took a different route: rather than excluding studies, it recalculated published light-water-reactor estimates with consistent system boundaries and performance assumptions. The published median, interquartile range and total range of 13, 23 and 220 g became 12, 17 and 110 g after harmonisation, which is where AR5's nuclear range of 3.7–12–110 g comes from. This does not prove that any single high estimate is wrong; it shows that much of the spread comes from differing assumptions (for example plant lifetime, capacity factor, enrichment method and ore grade) rather than from the technology. Warner & Heath also project that, depending on conditions, median emissions could be 9–110 g by 2050, so ore grade remains a legitimate open question for the future.

5.3 Opportunity-cost emissions (Jacobson 2009)

The argument. Jacobson adds emissions from the existing grid during the extra years a nuclear plant takes from planning to operation (10–19 years in his assumptions) compared with wind or solar. His total of 68–180 g combines a lifecycle component of 9–70 g with 59–106 g of opportunity-cost emissions.

How it is treated. This is not a disputed lifecycle measurement but a different quantity. SRREN only admitted studies using attributional lifecycle assessment and excluded consequential assessments because their results are fundamentally not comparable. Opportunity-cost emissions depend on what the alternative is, how fast it can be built and how the grid would otherwise evolve, so they belong in a planning comparison, not in a per-kWh lifecycle table. Whether the argument is right is a question about build times and system planning, which per-kWh data cannot settle.

5.4 Chernobyl death tolls

The death-rate differences in Figures 3 and 4 come almost entirely from the assumed Chernobyl toll. The estimates differ mainly in which population and which dose range they include:

- *Chernobyl Forum (IAEA/WHO/UNDP, 2005)*: up to about 4,000 eventual deaths among roughly 600,000 most-exposed people (emergency workers, evacuees, residents of the most contaminated areas). A further WHO estimate adds about 5,000 for lower-exposed populations in Belarus, Russia and Ukraine.
- *TORCH report (2006)*: 30,000–60,000 excess cancer deaths across Europe, using the linear no-threshold (LNT) model for very low doses. The authors warned that such predictions depend strongly on the risk factor used.
- *Greenpeace (2006)*: about 93,000 fatal cancers, a figure reported not to have been peer reviewed.
- *Yablokov, Nesterenko & Nesterenko (2009)*: 985,000 premature deaths between 1986 and 2004, derived from mostly Russian-language literature.

How they are treated. The LNT-based estimates are not shown to be false; they are untestable at the population level. UNSCEAR (2012) states that, because of uncertainties at low doses and the insufficient statistical power of epidemiological studies, it does not recommend multiplying very low doses by large numbers of people to estimate health effects. Critics such as Ian Fairlie argue that this was a reversal of UNSCEAR's earlier practice and that several studies do show effects near background dose levels. This is a genuine scientific disagreement about low-dose risk.

The Yablokov figure is treated differently. Balonov (2012) concluded that the book replaced analytical epidemiology with ecological comparisons and that this overestimated the number of victims by more than 800,000 deaths for 1987–2004. A review by Dreicer (2010) criticised the book for excluding many major technical studies and for setting aside the accepted methods for linking cause and effect. The New York Academy of Sciences stated that the volume was not new work and not commissioned by the Academy. In short: the 4,000–60,000 range reflects a real disagreement about low-dose risk; the 985,000 figure is rejected on methodological grounds by the published reviews cited here.

5.5 Hydro deaths

Hydro's 1.3 deaths/TWh is dominated by the 1975 Banqiao dam failure in China. OWID notes that without it, hydro's death rate would be about 0.04 deaths/TWh, comparable to nuclear, solar and wind. Hydro is therefore also a "fat tail" technology, just like nuclear.

6 Takeaways

- Even with the most pessimistic published inputs (288 g; ~10 deaths/TWh), nuclear stays below coal on both measures, below gas on emissions and below coal and oil on deaths. Against wind and solar it can lose under those inputs.
- The extreme numbers fall into three groups: real but site-specific (hydro methane), assumption-driven and narrowed by harmonisation (high nuclear lifecycle estimates, opportunity cost), and methodologically rejected (Yablokov).
- What per-TWh statistics cannot settle is how to weigh rare catastrophes, low-dose risk under LNT, waste governance, cost and build time.

Appendix: all numbers used

A1 Lifecycle emissions, IPCC SRREN (gCO₂eq/kWh), Figure 1

Source: Moomaw et al. (2011), SRREN Annex II, Table A.II.4.

Source	Min	25th	Median	75th	Max
Coal	675	877	1001	1130	1689
Oil	510	722	840	907	1170
Natural gas	290	422	469	548	930
Nuclear	1	8	16	45	220
Solar PV	5	29	46	80	217
Geothermal	6	20	45	57	79
CSP	7	14	22	32	89
Wind	2	8	12	20	81
Hydropower	0	3	4	7	43

A2 Lifecycle emissions, IPCC AR5 and worst cases (gCO₂eq/kWh), Figure 2

Item	Min	Median	Max	Source
Coal (pulverised)	740	820	910	Schlömer et al. (2014), AR5 Annex III, Tab. A.III.2
Gas (combined cycle)	410	490	650	same
Biomass (dedicated)	130	230	420	same
Solar PV (utility)	18	48	180	same
Hydropower	1	24	2200	same; max from Kemenes et al.
Nuclear	3.7	12	110	same; based on Warner & Heath (2012)
Wind (onshore)	7	11	56	same
Nuclear, Jacobson total	68	–	180	Jacobson (2009): lifecycle 9–70 + opportunity cost 59–106
Nuclear, Sovacool survey	1.4	66 (mean)	288	Sovacool (2008)
Nuclear, published LWR pool	–	13	220 (range)	Warner & Heath (2012), before harmonisation
Nuclear, harmonised LWR	–	12	110 (range)	Warner & Heath (2012), after harmonisation

A3 Deaths per TWh (accidents + air pollution), Figure 3

Source: Our World in Data, “What are the safest and cleanest sources of energy?” (Ritchie), drawing on Markandya & Wilkinson (2007) and Sovacool et al. (2016).

Source	Deaths/TWh	Note
Coal	24.6	
Oil	18.4	
Biomass	4.6	
Gas	2.8	
Hydropower	1.3	since 1965, incl. Banqiao 1975; ~0.04 without it

Source	Deaths/TWh	Note
Wind	0.04	
Nuclear	0.03	assumes 433 Chernobyl + 2,314 Fukushima deaths
Solar	0.02	

A4 Nuclear death-rate sensitivity, Figure 4

Formula: rate = (Chernobyl deaths + 2,314) / 96,876 TWh. Both the Fukushima toll and the cumulative generation (1965–2021) are OWID’s values.

Chernobyl estimate	Chernobyl deaths	Deaths/TWh	Source
OWID assumption	433	0.028	OWID (Ritchie)
Chernobyl Forum / WHO	4,000	0.065	IAEA/WHO/UNDP press release (2005)
WHO incl. lower-dose areas	9,000	0.117	WHO (2006): ~4,000 + ~5,000
TORCH low	30,000	0.334	Fairlie & Sumner, TORCH (2006)
TORCH high	60,000	0.643	Fairlie & Sumner, TORCH (2006)
Greenpeace 2006	93,000	0.984	Greenpeace (2006)
Yablokov et al. 2009	985,000	10.192	Yablokov et al., Ann. NY Acad. Sci. (2009)

A5 References

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